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Seeing and hearing quasi-static shear band localization in a sandstone

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The localisation of structural damage, in the form of faults and fractures, along a distinct and emergent fault plane is the key driving mechanism for catastrophic failure in the brittle Earth. However, due to the speed at which stable crack growth transitions to dynamic rupture, the precise mechanisms involved in localisation as a pathway to fault formation remain unknown. Understanding these mechanisms is critical to understanding and forecasting earthquakes, including induced seismicity, landslides and volcanic eruptions, as well as failure of man-made materials and structures. We used time-resolved synchrotron x-ray microtomography to image in-situ damage localisation at the micron scale and at bulk axial strain rates down to 10^{-7} s^{-1}. By controlling the rate of micro-fracturing events during a triaxial deformation experiment, we deliberately slowed the strain localisation process from seconds to minutes as failure approached. This approach, originally established to indirectly image fault nucleation and propagation with acoustic emissions, is completely novel in synchrotron x-ray microtomography and has enabled us to image directly processes that are normally too transient even for fast synchrotron imaging methods. Here, we first present the experimental apparatus and control system used to acquire the data, followed by damage localisation and shear zone development in a sample of Clashach sandstone viewed in unprecedented detail. Time-resolved microtomography images demonstrate a strong intrinsic correlation between shear and dilatant strain in the localised zone, with bulk shear strain accomodated by the nucleation and rotation of en-echelon tensile microcracks within a grain-scale shear band. Rotation is accompanied by antithetic to synthetic shear sliding of neighbouring crack surfaces as they rotate. The evolving 4D strain field, measured with incremental digital volume correlation between pairs of recorded x-ray tomographic volumes, independently confirm the correlation between shear and dilatant strain and show how strain localises spontaneously, first through exploration of several competing shear bands at peak stress before transitioning to failure along the optimally-oriented final fault plane. In order to 'ground-truth' inferences made from bulk measurements and seismic waves (the primary method of detecting deformation at the field-scale where direct imaging of the subsurface is impossible), we (a) compare rupture energy estimates from local slip measurements with those from bulk slip

data, and (b) use AE source location estimates to identify individual cracks and other local changes in the microstucture that may explain the AE source.